AFRL-RX-WP-TP-2008-4036

CLUTTER REMOVAL AND INVERSION OF EDDY-CURRENT IMPEDANCE DATA (POSTPRINT)

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DECEMBER 2006

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
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AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*
December 2006

2. REPORT TYPE
Conference Proceedings Postprint

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
CLUTTER REMOVAL AND INVERSION OF EDDY-CURRENT IMPEDANCE DATA (POSTPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62102F

6. AUTHOR(S)
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5d. PROJECT NUMBER
4349

5e. TASK NUMBER
RG

5f. WORK UNIT NUMBER
M04R1000

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Air Force Materiel Command
United States Air Force

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RX-WP-TP-2008-4036

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RXLP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RX-WP-TP-2008-4036

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Conference paper published in the Proceedings of the 23rd Annual Review of Progress in Applied Computational Electromagnetics. Paper contains color.

 PAO Case Number: AFRL/WS 07-0071, 23 Jan 2007.

14. ABSTRACT
A wide variety of problems in computational electromagnetics have been successfully solved using a volume-integral approach along with conjugate-gradient methods. The volume integral algorithm is particularly well suited to the notion of model-based inversion of eddy-current impedance data in the arena of quantitative nondestructive evaluation (NDE). The first step in preparing data for inversion is to remove 'clutter,' which can originate in systematic measurement errors, or simply be a large background signal. In this paper we develop a systematic analytical technique to remove such clutter, which then allows the resulting impedance data to be fed into a nonlinear least-squares inversion algorithm, NLSE. The computational engine for the analysis is VIC-3D©, a proprietary volume-integral code.

15. SUBJECT TERMS
Volume-integral equations, electromagnetic nondestructive evaluation, clutter, model-based inversion

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
Unclassified	Unclassified	Unclassified	SAR	14	Kumar Jata
					19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

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Abstract: A wide variety of problems in computational electromagnetics has been successfully solved using a volume-integral approach along with conjugate-gradient methods. The volume-integral algorithm is particularly well-suited to the notion of model-based inversion of eddy-current impedance data in the arena of quantitative nondestructive evaluation (NDE). The first step in preparing data for inversion is to remove 'clutter,' which can originate in systematic measurement errors, or simply be a large background signal. In this paper we show that a simple model for such clutter allows the impedance data to be rendered usable in a nonlinear least-squares inversion algorithm, NLSE. The computational engine for the analysis is **VIC-3D**©, a proprietary volume-integral code.

Keywords: volume-integral equations, electromagnetic nondestructive evaluation, clutter, model-based inversion

1. Introduction

A Benchmark Validation Experiment: Several years ago Victor Technologies, under a contract with the Electric Power Research Institute (EPRI),[1] was tasked to validate its proprietary code, **VIC-3D**©[1][2], against benchmark data supplied by the Westinghouse Research Labs. Though it was not the intent of the benchmark test to do anything more than validate the ability of **VIC-3D**© to accurately create 'forward' models of the experimental setups, several of the experiments yielded an excellent opportunity to develop and test the clutter-rejection and model-based inversion ideas that are presented in this paper. They further allowed us to develop ideas about the detectability of anomalies, which is discussed in this paper.

[1] **Calculation Using VIC-3D© Eddy-Current Modeling Software**, Final Report on Agreement No. WOS537-02 between Electric Power Research Institute, Inc., and Victor Technologies, LLC, 14 February, 1999

Experimental data were taken on a 0.048 inch-thick Inconel 600 plate, which is nonmagnetic (relative permeability, $\mu = 1$), and has a conductivity of $\sigma = 9.86 \times 10^5$ S/m. A notch is introduced into the 'outer diameter' of the plate, which means the surface opposite to the probe. A coil is excited at 100kHz, and 200kHz, and is scanned tranversely to the slot, such that impedances are measured at 250 points, each separated by 4 mils (see Figure 1). The OD of the coil is 0.112 in.,

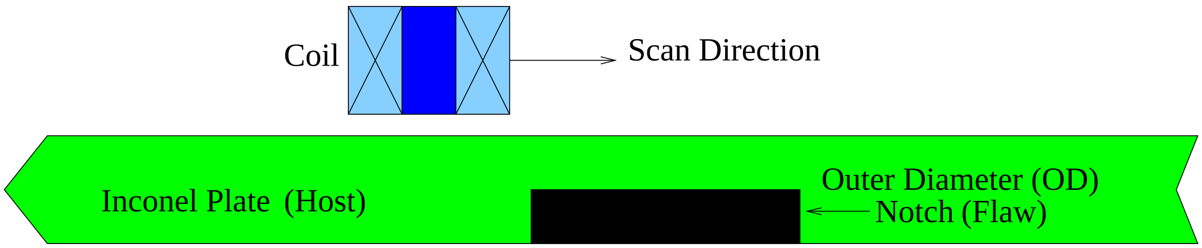

Figure 1: Illustrating the setup for the experiment and model calculations.

the ID is 0.034 in., the height is 0.048 in., and there are 131 turns in the coil. The experiment is run with a coil lift-off of 0.015 in. above the plate.

The impedance data were measured by Warren Junker of the Westinghouse Research Labs, using a Hewlett-Packard 4194A impedance analyzer, and recorded to six significant digits, which implies a dynamic range of 120 dB.

In Section 2 we present results for clutter rejection and inversion of data at 100 kHz for a transverse outer-diameter slot, and in Section 3 we use clutter rejection in a study of anomaly detectability with data at 200 kHz for a ligatured outer-diameter slot. These examples are chosen because the flaw signal is difficult to measure in the presence of considerable clutter. The paper ends with comments and conclusions.

2. Outer-Diameter Slot at 100kHz.

The 'host-only' impedance, i.e., the impedance measured when the probe is well away from the flaw, was measured to be $Z_{\text{host}} = 4.05115 + j10.8770\ \Omega$. When Z_{host} is subtracted from all 250 data points, the result is the 'anomaly signal' shown in Figure 2. Note the significant 'clutter' in the resistance data that is produced by a systematic error of unknown origin. The most likely sources of this clutter, as well as those for the ligatured crack of Figure 5 in Section 3, are uneven liftoff, plate thickness, or electronics drift.

In order to determine the 'flaw signal,' we subtract the clutter from the anomaly signal. This is done by first modeling the clutter with a simple mathematical expression, in this case by the piecewise linear functions:

$$
\begin{aligned}
R_{\text{clutter}} &= \begin{array}{ll} 0.0045 - 0.00225 \times (\text{pos} + 0.5) & \text{if pos} \leq -0.1 \\ 0.0036 + 0.0066 \times (\text{pos} + 0.1) & \text{otherwise} \end{array} \\
X_{\text{clutter}} &= -0.0005 + 0.0005 \times (\text{pos} + 0.5)\ , \qquad (1)
\end{aligned}
$$

where 'pos' designates the probe position. These functions approximate the asymptotic response when the probe is well away from the flaw. When the clutter signal of (1) is subtracted from the

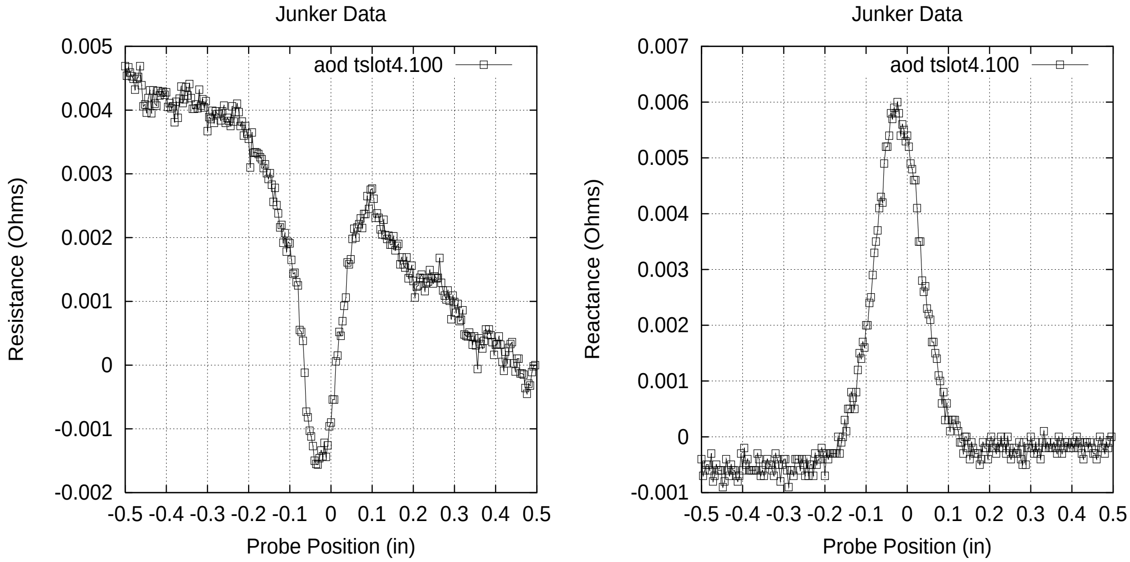

Figure 2: Original data as supplied by Warren Junker of the Westinghouse Research Labs. Note the significant 'clutter' in the resistance data, produced by a systematic error.

data of Figure 2, we get the 'processed' data of Figure 3. It is now clear that the original data resulted from a scan over a notch-type flaw.

We assume that the flaw is a rectangular paralleliped notch that breaks the back surface of the workpiece, i.e., the surface away from the probe. The problem then is to determine the size of the notch, namely its length, width, and height. In order to do that, we apply the processed data of Figure 3 as the input to NLSE, the nonlinear least-squares parameter estimator that is a part of **VIC-3D©**'s post-processor system. The three parameters are, of course, the length, width, and height of the notch. We could extend the model parameters to include coil-offset from the centerline of the flaw, or coil-liftoff from the host, but we choose to keep this example simple. We have used these other parameters successfully in other related inverse problems.

In order to perform the inversion, we first use **VIC-3D©** in the 'forward mode' to generate a two-point interpolation table for length and width (holding the height at 0.025 in). The model data for this table are obtained by scanning the probe longitudinally over the center of the crack, starting at -0.5 in and ending at +0.496 in, in 0.004-inch increments. This gives 250 data points which agree with the input data for each of the four parametric values in the interpolation table. NLSE, then, computes the values that it needs during the reconstruction process by a linear interpolation within this table. The results are: length = 0.2277 in, width = 0.0049 in, and height = 0.025 in.

When we repeat the inversion experiment, this time holding the height of the flaw to 0.024 in, we get length = 0.2424, and width = 0.0050. In the first case (height = 0.025) the final norm of the residuals is 0.8112711×10^{-2}, whereas with the height = 0.024 the norm is equal to 0.8522527×10^{-2}, which is 5% larger. The effect of this is discussed next.

When we use **VIC-3D©** in the forward mode to compute the scanned impedances, given notches of the size just determined, and compare these results with the input data of Figure 3, we get the results shown in Figure 4. Clearly, the clutter-removal algorithm, together with **VIC-3D©**, has been effective. The resistance curve for the case of the notch with height = 0.025 falls closer to the negative peak of the input data than does the curve for the other notch. The reactance curves of the two notches, however, are virtually indistinguishable. This suggests that it is the better fit

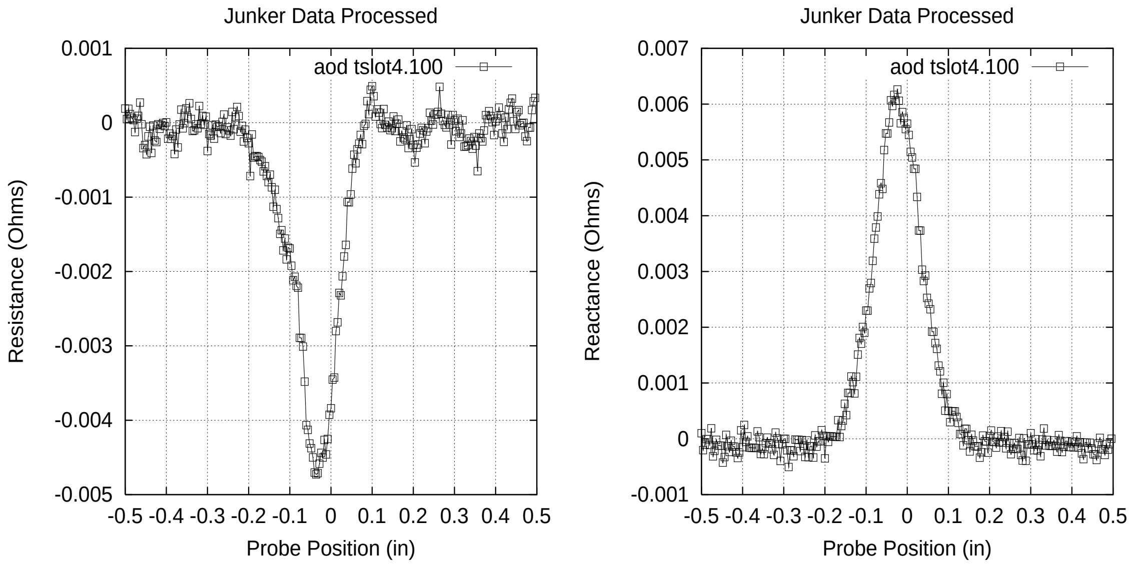

Figure 3: Showing the original Junker data with the clutter removed.

of the resistance data that gives the 0.025-inch notch the smaller residual-norm compared to the 0.024-inch notch.

Table 1 compares the nominal, measured, and computed data for these notches.

Table 1: Comparison of Nominal, Measured and Computed values for the Length (L), Width (W) and Depth (D) of the reconstructed A4 notches with two different depths. The measured data were supplied by W. Junker from salastic molds.

L Nom. (in.)	L Meas. (in.)	L Comp. (in.)	W Nom. (in.)	W Meas. (in.)	W Comp. (in.)	D Nom. (in.)	D Meas. (in.)	D Comp. (in.)
0.25	0.252	0.2277	0.005	0.007	0.0049	0.020	0.0238	0.025
0.25	0.252	0.2424	0.005	0.007	0.0050	0.020	0.0238	0.024

3. Ligatured Outer-Diameter Slot at 200kHz

We continue with another example from the data provided by Warren Junker of Westinghouse Research Labs for our EPRI contract. In this case we modeled an ‘outer-diameter’ flaw comprising 5 notches and 4 gaps, which could model a crack with periodic contact points between the surfaces, i.e., a partially closed crack of the type that we will consider further in this report.

The geometry of the test setup and model is the same as shown in Figure 1, except that the flaw is not a single notch, but a series of notches and gaps. The notches are each 0.041 inches long, 0.0065 inches wide, and 0.0138 inches deep. The plate is 0.048 inches thick, so this would be an outer-diameter flaw that extends 28.75% into the host. The gaps (ligatures) are 0.0066 inches long. Hence, the crack is 0.2314 inches long, and is 11.4% closed.

The original measured impedance data and **VIC-3D©** model results at 200kHz are shown in Figure 5. We model the clutter signal by the piecewise linear functions:

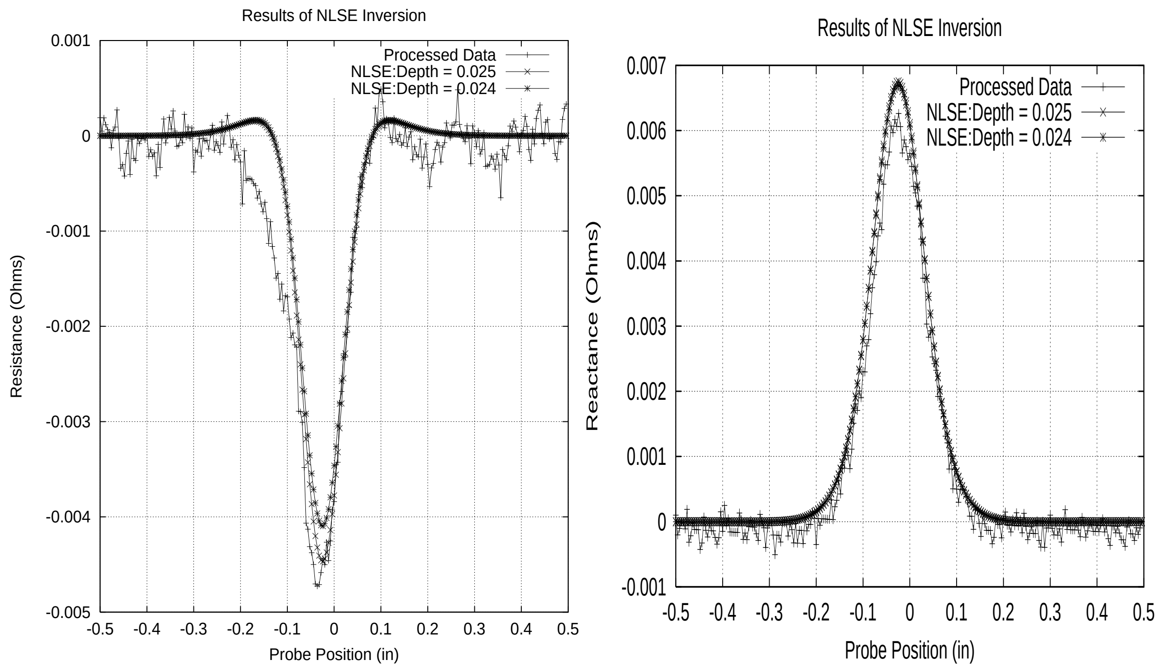

Figure 4: Showing the effects of inverting the processed original data to reconstruct the flaw.

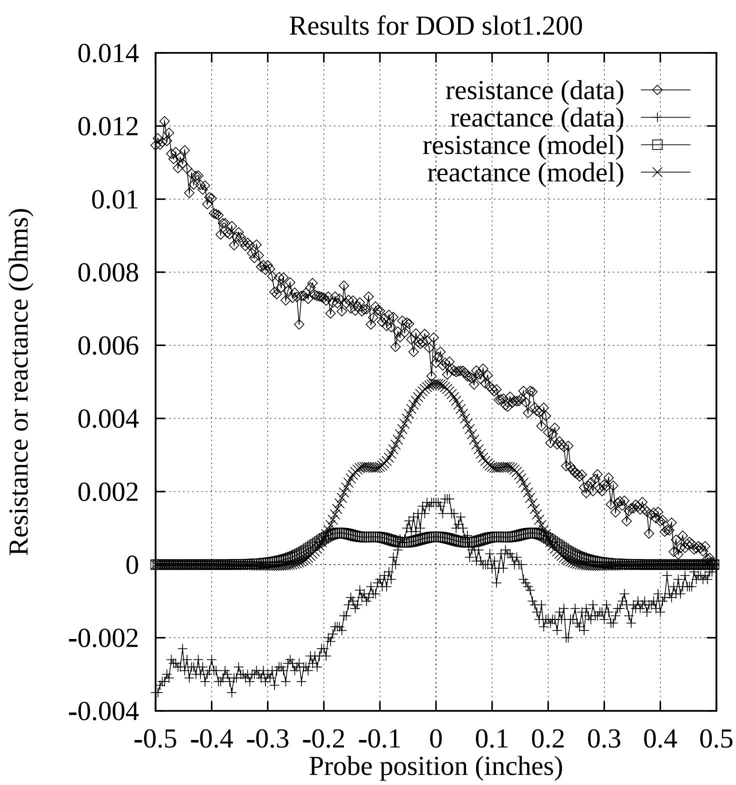

Figure 5: Original measured impedance data and **VIC-3D**© model results for a ligatured crack.

$$\begin{aligned}
R_{\text{clutter}} &= 0.0117 - 0.01719 \times (\text{pos} + 0.5) && \text{if pos} \leq -0.244 \\
&= 0.0073 - 0.00986 \times (\text{pos} + 0.244) && \text{otherwise} \\
X_{\text{clutter}} &= -0.003 && \text{if pos} \leq 0.1 \\
&= -0.003 + 0.0075 \times (\text{pos} - 0.1) && \text{otherwise}
\end{aligned} \tag{2}$$

When this signal is subtracted from the measured data of Figure 5, we get the results shown in the top portion of Figure 6. The Bezier-filtered and processed resistance data are shown in the bottom portion of Figure 6. The ripples that appear in the **VIC-3D**©-generated model results and in the original data over the peak range are a manifestation of the existence of the periodic contact points or 'ligands.'

At 200 kHz, the free-space impedance of the coil that was used to take these data is $4.02 + j21.91\Omega$, and the on-plate, host-only, impedance is $4.78 + j21.29\Omega$. Figure 6 shows that we can easily resolve a value of $\delta R = 0.0001\Omega$ (using the Bezier filter) and $\delta X = 0.0002\Omega$. This means that we have an effective dynamic range of $20\log(4.78/0.0001) = 93.6$ dB for resistance, and $20\log(21.29/0.0002) = 100.5$ dB for reactance. Hence, we have significantly gained dynamic range by the process of clutter removal, and what was clearly an undetectable flaw-resistance value in Figure 5 becomes quite detectable in Figure 6. The results of Figure 6 can then be used successfully in an inversion process.

If we believe in the 'principle of conservation of dynamic range,' that dynamic range in data can neither be created nor destroyed, then we must conclude that the Hewlett-Packard 4194A impedance analyzer had the requisite dynamic range of 100dB, but that the original data of Figure 5 obscured this fact because of the clutter. Once the clutter was removed the 'true-anomaly data' were then manifest.

4. Comments and Conclusions

Model-based inversion, which is playing an increasingly important role in the development of advanced techniques of electromagnetic NDE [3], depends crucially on the elimination of 'clutter,' as well as on the rapid solution of forward problems, and the development of accurate models of anomalies that can be described with a few parameters. We have shown that the volume-integral approach works well within this framework, and that sophisticated inversion algorithms can be generated through the volume-integral formulation. Furthermore, we have shown an analytical 'clutter-rejection' algorithm that can be automated, without requiring human intervention. The promise, therefore, is that model-based inversion will evolve quickly into a reliable tool for the analysis of pitting and corrosion phenomena in areas as diverse as nuclear power plants and aerospace structures.

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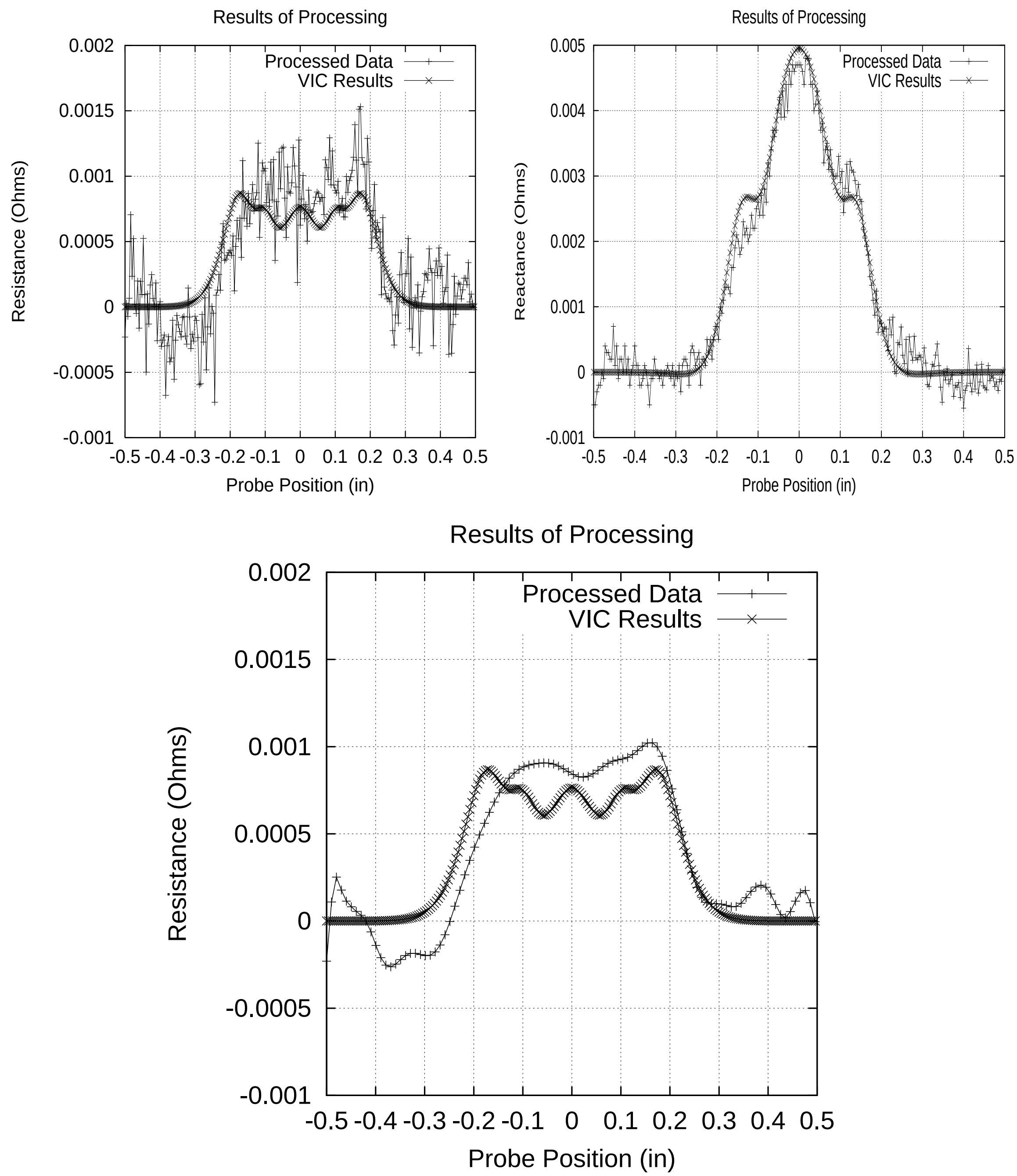

Figure 6: Measured data with the clutter removed, together with the same **VIC-3D©** model results. top left: resistance, top right: reactance. Bottom: Measured resistance data with the clutter removed, and passed through a Bezier filter.

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